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(54) **MAGNETIC STEEL SHEET HAVING EXCELLENT MAGNETIC PROPERTIES AND METHOD FOR MANUFACTURING THE SAME**

(57) A grain-oriented electromagnetic steel sheet comprising an electromagnetic steel sheet with recesses, subdividing magnetic domains, formed by irradiating the surface of the electromagnetic steel sheet with a pulsed laser beam, wherein rows of recesses provided along the widthwise direction of the steel sheet are provided at predetermined spacings in the rolling direction and the recesses satisfy the following requirements:

length of recesses in rolling direction, dl: 50 μm ≤ dl ≤ 300 μm,
length of recesses in widthwise direction of sheet, dc: 100 μm ≤ dc ≤ 3000 μm, provided that dl/dc < 1
depth of recess, d: 10 μm ≤ d ≤ 30 μm,
row pitch of recess in rolling direction, Pl: 3 mm ≤ P1 ≤ 10 mm, and
pitch of recesses in widthwise direction of sheet, Pc: dc - 50 μm ≤ Pc ≤ dc + 50 μm,

and a process for producing a grain-oriented electromagnetic steel sheet, characterized by focusing a pulsed laser beam in a rectangular or elliptical form on the surface of an electromagnetic steel sheet to form the recesses.

EP 0 870 843 A1

Description

Technical Field

This invention relates to a grain-oriented electromagnetic steel sheet possessing excellent magnetic properties and, more particularly, to a grain-oriented electromagnetic steel sheet possessing excellent magnetic properties which, even when subjected to strain release annealing, does not lose the excellent iron loss properties.

Background Art

Reduction in iron loss has been required of grain-oriented electromagnetic steel sheets from the viewpoint of energy saving. In order to reduce the iron loss, Japanese Examined Patent Publication Kokoku No. 58-26405 discloses a method wherein magnetic domains are subdivided by laser beam irradiation. According to this method for reducing iron loss, a stress is introduced into a grain-oriented electromagnetic steel sheet by the reactive force of a thermal shock wave created by laser beam irradiation to subdivide magnetic domains, thereby lowering eddy-current loss while suppressing an increase in hysteresis loss. This method, however, has a problem that the strain introduced by the laser beam irradiation disappears upon annealing, causing the effect attained by the subdivision of magnetic domains to be lost. Therefore, although the above method can be used for laminated core transformers not requiring strain release annealing, it cannot be used for wound core transformers requiring strain release annealing.

For this reason, in order to improve the magnetic properties of the grain-oriented electromagnetic steel sheet while maintaining the iron loss reduction effect even after strain release annealing, various methods have been proposed wherein a change in geometry to an extent exceeding the stress strain level is provided in the steel sheet to change the permeability, thereby subdividing magnetic domains. Examples of these methods include one wherein a steel sheet is pressed by a sprocket roll to form grooves or spot recesses on the surface of the steel sheet (see Japanese Examined Patent Publication Kokoku No. 63-44804), one wherein recesses are formed by chemical etching on the surface of a steel sheet (see U.S. Patent No. 4750949) and one wherein grooves are formed by a Q switch CO_2 laser beam on the surface of a steel sheet (see Japanese Unexamined Patent Publication Kokai No. 7-220913).

Among the above conventional methods, the mechanical method using a sprocket roll is disadvantageous in that the sprocket is abraded in a short time due to high hardness of the electromagnetic steel sheet and the iron loss value cannot be satisfactorily lowered as compared with the method for controlling magnetic domains by laser energy which does not change the geometry. The chemical etching method, although it does not suffer from the problem of the abrasion of the sprocket, involves more a complicated process than the mechanical method and in addition has room for improvement in iron loss reduction. The method wherein grooves are formed by a Q switch CO_2 laser beam on the surface of a steel sheet forms recesses in a non-contact manner. Therefore, this method does not suffer from the problem of the abrasion of the sprocket and the problem of the complicated process. In this method, however, the optimal geometry of the recesses has not been investigated in detail, and there is room for improvement in iron loss reduction.

Disclosure of the Invention

The present invention solves the above problems and provides a grain-oriented electromagnetic steel sheet, possessing excellent magnetic properties, which has a lower iron loss value than the conventional grain-oriented electromagnetic steel sheet and does not lose its excellent magnetic properties even at high temperatures, and a process for producing the same.

Specifically, in the present invention, a pulsed laser beam is applied to the surface of an electromagnetic steel sheet to form recesses satisfying the following requirements and offering such an effect that the formation of the recesses subdivides magnetic domains to reduce the iron loss and, in addition, even when the steel sheet is subjected to strain release annealing, the magnetic domain subdivision effect does not disappear.

The recesses are formed so that rows of recesses arranged along the widthwise direction (a direction normal to the rolling direction) of the steel sheet are provided in the rolling direction at given spacings and, in addition, the recesses satisfy the following requirements:

length of recesses in rolling direction, dl: $50\ \mu m \le dl \le 300\ \mu m$,
length of recesses in widthwise direction of sheet, dc: $100\ \mu m \le dc \le 3000\ \mu m$, provided that $dl/dc < 1$
depth of recess, d: $10\ \mu m \le d \le 30\ \mu m$,
row pitch of recesses in rolling direction, Pl: $3\ mm \le P1 \le 10\ mm$, and
pitch of recesses in widthwise direction of sheet, Pc: $dc - 50\ \mu m \le Pc \le dc + 50\ \mu m$.

In particular, a great feature of the present invention is that the iron loss can be reduced by specifying the recess

pitch Pc in the widthwise direction of the steel sheet, among the above requirements, in connection with the recess length dc in the widthwise direction of the steel sheet.

Brief Description of the Drawings

Fig. 1 is a schematic perspective view showing recesses formed on the surface of the grain-oriented electromagnetic steel sheet according to the present invention;
Fig. 2 (a) is a partially enlarged plan view of Fig. 1;
Fig. 2 (b) is a cross-sectional view taken on line X-X of Fig. 2;
Fig. 3 is a schematic front view of an apparatus for forming recesses according to the present invention;
Fig. 4 is a waveform diagram showing one example of the results of measurement of a waveform of a pulsed laser beam emitted from a Q switch CO_2 laser oscillator shown in Fig. 3;
Fig. 5 (a) is a diagram showing the sectional form of a circular focused beam focused on an electromagnetic steel sheet and the intensity profile in each section;
Fig. 5 (b) is a diagram showing the sectional form of a rectangular focused beam focused on an electromagnetic steel sheet and the intensity profile in each section;
Fig. 6 (a) is a schematic diagram of an enlarged plan photograph showing one example of recesses formed by means of a circular focused beam shown in Fig. 5 (a);
Fig. 6 (b) is a cross-sectional view taken on line X-X of Fig. 6 (a);
Fig. 6 (c) is a cross-sectional view taken on line Y-Y of Fig. 6 (a);
Fig. 6 (d) is a schematic diagram of an enlarged photograph showing one example of recesses formed by means of a rectangular focused beam shown in Fig. 5 (b);
Fig. 6 (e) is a cross-sectional view taken on line X-X of Fig. 6 (d);
Fig. 6 (f) is a cross-sectional view taken on line Y-Y of Fig. 6 (d);
Fig. 7 (a) is a diagram showing the relationship between the recess pitch (Pc) in the widthwise direction of the steel sheet after strain release annealing and the percentage iron loss improvement in the case where the recess length (dc) in the widthwise direction of the steel sheet is 140 μm; and
Fig. 7 (b) is a diagram showing the relationship between the recess pitch (Pc) in the widthwise direction of the steel sheet after strain release annealing and the percentage iron loss improvement in the case where the recess length (dc) in the widthwise direction of the steel sheet is 270 μm.

Best Mode for Carrying Out the Invention

Next, the best mode for carrying out the invention will be described.

At the outset, a steel sheet produced based on the present invention, that is, a steel sheet having recesses 6 formed on the surface 2 of a grain-oriented electromagnetic steel sheet 1 in rows 5, is schematically shown in Fig. 1.

The recesses 6 will be described with reference to Figs. 2 (a) and (b).

Fig. 2 (a) is a partially enlarged plan view of Fig. 1 wherein, in connection with the recesses 6, dc represents the length of the recess in the widthwise direction of the steel sheet, Pc the recess pitch in the widthwise direction of the steel sheet, and Pl the row pitch of the recesses in the rolling direction. Fig. 2 (b) is a cross-sectional view taken on line X-X of Fig. 1, wherein recesses 6 are successively provided and a protrusion 7 is provided between adjacent recesses 6, thereby giving a comb-like shape on the whole.

On the other hand, the back surface 3 is smooth, and, in the lamination of electromagnetic steel sheets, no gap is created between the steel sheets, thus avoiding a lowering in percentage of lamination.

According to the present invention, the geometry of the recesses are specified as follows.

When the length of the recess in the rolling direction of the electromagnetic steel sheet, dl, is less than 50 μm, the effect of reducing the iron loss is lowered, while when the length exceeds 300 μm, the magnetic flux density is significantly lowered. For this reason, the dl value should be 50 μm ≤ dl ≤ 300 μm.

When the length of the recess in the widthwise direction of the steel sheet, dc, is less than 100 μm, application of pulses at a very high speed is required for successively forming the recesses. This is difficult to accomplish and is not realistic. On the other hand, when the length of the recess in the widthwise direction of the steel sheet, dc, exceeds 3000 μm, the effect of reducing the iron loss is lowered. For this reason, the dc value should be 100 μm ≤ dc ≤ 3000 μm.

When the recess depth d is less than 10 μm, the effect of reducing the iron loss is deteriorated, while a d value exceeding 30 μm deteriorates the effect of reducing the iron loss and, in addition, results in significantly deteriorated magnetic flux density. Therefore, the d value should be 10 μm ≤ d ≤ 30 μm.

When the row pitch of recesses in the rolling direction, Pl, is less than 3 mm or exceeds 10 mm, the effect of reducing the iron loss is deteriorated. Therefore, the Pl value should be 3 mm ≤ Pl ≤ 10 mm.

When the recess pitch in the widthwise direction of the steel sheet, Pc, is in the range of from (dc - 50 μm) to (dc +

50 µm), the effect of reducing the iron loss becomes maximum. For this reason, the Pc value is limited to this range. Further, regarding the geometry of the recess, when the length of the recess in the rolling direction, dl, is smaller than the length of the recess in the widthwise direction of the steel sheet, dc, that is, when the recess is in a rectangular or elliptical form having a major axis in the widthwise direction of the steel sheet, the effect of improving the iron loss is better than that in the case where the recess is circular. Therefore, the ratio of dl to dc, that is, dl/dc, should be less than 1.

The above ranges were determined by investigating the relationship between the recess pitch in the widthwise direction of the steel sheet, Pc, the percentage improvement in iron loss, and the geometry of recesses as follows.

The surface of a grain-oriented electromagnetic steel sheet was irradiated with a circular focused light beam having a diameter of 140 µm and a rectangular focused light beam having a size of 90 x 270 µm from a pulsed laser oscillator while successively varying the recess pitch Pc in the widthwise direction of the steel sheet to form recesses. After the formation of the recesses, the steel sheet was held at a temperature of 800°C for 2 hr, thereby conducting strain release annealing. The percentage improvement in iron loss and the degree of deterioration in magnetic flux density in the recesses were measured. The results are shown in Figs. 7 (a) and (b) for comparison of the two cases. The percentage improvement in iron loss is the proportion of the improved iron loss value to the initial iron loss value.

From the above drawings, the present inventors have confirmed that when the recess pitch Pc in the widthwise direction of the steel sheet is in the range of from (dc - 50 µm) to (dc + 50 µm) independently of whether the recess is circular or elliptical, the percentage improvement in iron loss is large, that is, the iron loss value is significantly lowered. Further, they have found that when the recess pitch Pc in the widthwise direction of the steel sheet is substantially equal to the length dc of the recess in the widthwise direction of the steel sheet, the percentage improvement in iron loss becomes a maximum.

Comparison of the maximum value of the percentage improvement in iron loss in the case of a circular recess shown in Fig. 7 (a) with the maximum value of the percentage improvement in iron loss in the case of an elliptical recess shown in Fig. 7 (b) shows that the elliptical recess can offer a higher percentage improvement than the circular recess. This is because recesses having a narrow, sharp shape in the rolling direction and a wide shape in the widthwise direction of the steel sheet can offer a better magnetic domain subdivision effect.

That is, it has been found that bringing the recess depth d to the range of 10 to 30 µm and, at the same time, the formation of a rectangular or elliptical recess having a major axis in the widthwise direction of the steel sheet, even when strain release annealing is carried out, can greatly reduce the iron loss value as compared with the prior art technique. The present invention has been completed based on this finding.

The process for producing a steel sheet according to the present invention will be described. In the present invention, a pulsed laser oscillator, such as a CO_2 laser oscillator or a YAG laser oscillator, is used, and a laser beam having a pulse width of not more than 30 µsec is focused, in a substantially rectangular or elliptical form, on the surface of the steel sheet, elongated in the widthwise direction thereof to form recesses. When the pulse width exceeds 30 µsec, the recess formability (depth d) is deteriorated due to heat transfer loss.

Fig. 3 is a schematic diagram showing a recess forming apparatus including the above pulsed laser oscillator.

At the outset, a pulsed laser beam LB is emitted from a pulsed laser oscillator 11, for example, a Q switch CO_2 laser oscillator, reflected by means of a plane total reflection mirror 13 provided in front of a beam emitting port of the oscillator, and enters a polygon mirror 15 provided at a position facing the plane total reflection mirror 13.

Subsequently, a polygon mirror 15 is rotated to scan the pulsed laser beam LB in the widthwise direction of the electromagnetic steel sheet 1.

The pulsed laser beam LB then enters a parabolic mirror 16 disposed just above the steel sheet, and the reflected light beam is focused on the surface of the electromagnetic steel sheet 1 to form recesses. The recess pitch Pc in the widthwise direction of the steel sheet is regulated by the frequency of the pulsed laser and the number of revolutions of the polygon mirror 15. The recess pitch Pl in the rolling direction is regulated by the number of revolutions per minute of the polygon mirror 15 and the feed rate of the steel sheet.

The pulsed laser has a waveform shown in Fig. 4. As shown in the drawing, the initial spiked section A is a giant pulse oscillated section characteristic of par minute a Q switch laser, and the half value width is 10 nsec to 1 µsec. This Q switch CO_2 laser pulse has a long tail section B after the initial spike. The maximum length of the tail section B is about 30 µsec. The maximum value of the pulse repetition frequency is up to about 100 kHz in the case of Q switch oscillation using a conventional continuous wave oscillation CO_2 laser. When the frequency is lowered from this value, in a region down to a pulse repetition frequency of about 20 kHz, the pulse energy is substantially in inverse proportion to the pulse repetition frequency, that is, a constant average laser output can be provided.

The pattern of the pulsed laser beam focused on an electromagnetic steel sheet and the intensity profile are shown in Figs. 5 (a) and (b).

Fig. 5 (a) is for a circular focused beam having a diameter of 140 µm, and Fig. 5 (b) is for a rectangular focused beam having a size of 90 x 270 µm. When the formation of a rectangular focused beam is contemplated, in the apparatus shown in Fig. 3, a cylindrical lens 14 is disposed between the plane total reflection mirror 13 and the polygon mir-

ror 15. A cylindrical mirror may be used instead of the cylindrical lens.

In this case, a row of recesses is formed by using a circular focused beam having a diameter of 140 μm shown in Fig. 5 (a) so as to provide a recess pitch Pc in the widthwise direction of the steel sheet of 125 μm is shown in Figs. 6 (a), (b), and (c). Fig. 6 (a) is a schematic diagram showing an enlarged photograph of the row of recesses taken from above. The recess length dc is about 140 μm.

Fig. 6 (b) is a cross-sectional view taken on line X-X of Fig. 6 (a), Fig. 6 (c) a cross-sectional view taken on line Y-Y of Fig. 6 (a). These drawings show the results of measurement of the sectional form of the row of recesses with a profile meter. The average recess depth is about 30 μm.

In Fig. 6 (b), the depthwise direction of the recesses is enlarged 14 times the longitudinal direction of the recesses.

Likewise, a row of recesses formed by using a rectangular focused beam having a major axis of about 270 μm and a minor axis of 90 μm shown in Fig. 5 (b) so as to provide a recess pitch Pc in the widthwise direction of the steel sheet of 270 μm is shown in Figs. 6 (d), (e), and (f). Fig. 6 (d) is a schematic diagram showing an enlarged photograph of the row of recesses taken from above. Fig. 6 (e) is a cross-sectional view taken on line X-X of Fig. 6 (d), Fig. 6 (f) a cross-sectional view taken on line Y-Y of Fig. 6 (d). These drawings show the results of measurement of the sectional form of the row of recesses with a profile meter. The average recess depth is substantially equal to that in the case of recesses formed using a circular focused beam having a diameter of 140 μm and is about 30 μm.

The recess depth d is regulated by the energy of a laser pulse.

As described above, and as shown in Fig. 7 (b), the rows of recesses, as shown in Figs. 6 (d) to (f), formed based on the conditions specified in the present invention, even when subjected to strain release annealing, do not cause the disappearance of the magnetic domain subdivision effect and in addition can offer further improved iron loss properties.

Example

Rectangular (invention) and circular and continuous groove (conventional) recesses were formed on the surface of a grain-oriented electromagnetic steel sheet (width: 900 mm, thickness: 0.23 mm). The applied pulsed laser was such that the output was 5 kW, the pulse repetition frequency was 100 kHz, the focused beam size was 90 x 270 μm, and the recesses had the following dimensions.

	Invention (Rectangular focusing)	Conventional (Circular focusing)	Conventional (Continuos groove)
Recess length in rolling direction, dl	90 μm	140 μm	400 μm
Recess length in widthwise direction of steel sheet, dc	270 μm	140 μm	-
Recess depth, d	25 μm	25 μm	25 μm
Row pitch of recesses in rolling direction, Pl	6 mm	5 mm	5 mm
Recess pitch in widthwise direction of steel sheet, Pc	270 μm	140 μm	300 μm
Percentage improvement in iron loss	14%	11%	5 to 8%

After the formation of the recesses, strain release annealing (800°C, 2 hr) was carried out, and the percentage improvement in iron loss was measured. As a result, the grain-oriented electromagnetic steel sheet according to the present invention had a percentage improvement in iron loss of 14%, whereas, in the conventional examples, the percentage improvement in iron loss was 11% or 8%.

Industrial Applicability

As is apparent from the foregoing detailed description, the grain-oriented electromagnetic steel sheet of the present invention can provide a higher percentage improvement in iron loss (for example, 12 to 14%) than a grain-oriented electromagnetic steel sheet with recesses created by the conventional pulsed laser irradiation. This can contribute to a fur-

ther improved efficiency of transformers, motors and other equipment and markedly reduced cost, so that the present invention is very useful from the viewpoint of industry.

Claims

1. A grain-oriented electromagnetic steel sheet possessing excellent magnetic properties, the grain-oriented electromagnetic steel sheet comprising an electromagnetic steel sheet with recesses formed on the surface thereof by irradiation with a pulsed laser beam, characterized in that the recesses satisfy the following requirements:

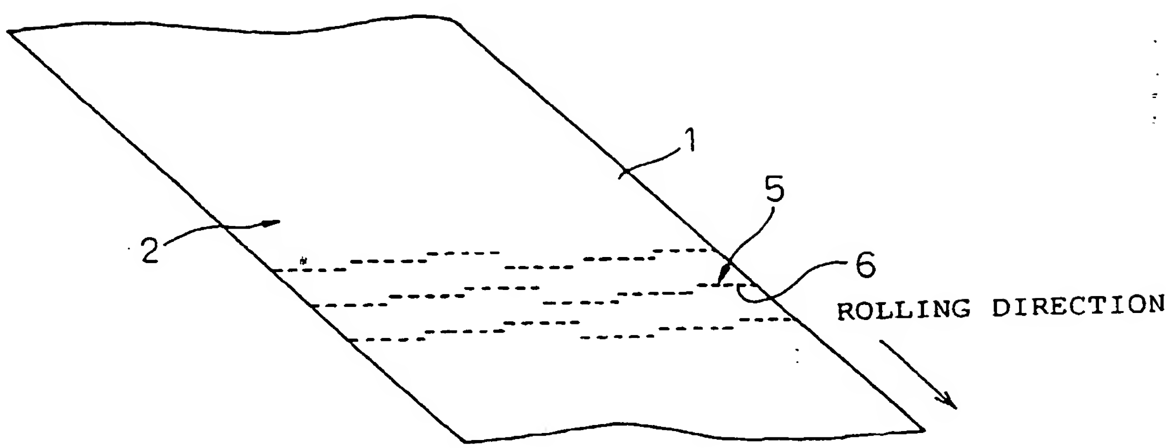
   rows of recesses provided along the widthwise direction of the steel sheet being provided at predetermined spacings in the rolling direction; and
   the recesses having the following geometry:
   length of recesses in rolling direction, dl: 50 μm $\leq$ dl $\leq$ 300 μm,
   length of recesses in widthwise direction of sheet, dc: 100 μm $\leq$ dc $\leq$ 3000 μm, provided that dl/dc < 1
   depth of recess, d: 10 μm $\leq$ d $\leq$ 30 μm,
   row pitch of recess in rolling direction, Pl: 3 mm $\leq$ P1 $\leq$ 10 mm, and
   pitch of recesses in widthwise direction of sheet, Pc: dc - 50 μm $\leq$ Pc $\leq$ dc + 50 μm.

2. A process for producing a grain-oriented electromagnetic steel sheet possessing excellent magnetic properties by irradiating the surface of an electromagnetic steel sheet with a pulsed laser beam to form recesses on the surface thereof, said process comprising the steps of:

   focusing a rectangular or elliptical pulsed laser beam on the surface of the electromagnetic steel sheet to form a plurality of recesses having a geometry satisfying the following requirements on the surface of the steel sheet in the widthwise direction thereof:
   length of recesses in rolling direction, dl: 50 μm $\leq$ dl $\leq$ 300 μm,
   length of recesses in widthwise direction of sheet, dc: 100 μm $\leq$ dc $\leq$ 3000 μm, provided that dl/dc < 1
   depth of recess, d: 10 μm $\leq$ d $\leq$ 30 μm, and
   pitch of recesses in widthwise direction of sheet, Pc: dc - 50 μm $\leq$ Pc $\leq$ dc + 50 μm; and
   moving the pulsed laser beam in the rolling direction of the surface of the steel sheet at the above pitch and focusing the pulsed laser beam on the surface of the steel sheet to form the plurality of recesses on the surface of the steel sheet in the widthwise direction thereof:
   row pitch of recesses in rolling direction, Pl: 3 mm $\leq$ P1 $\leq$ 10 mm.

3. The process according to claim 2, wherein the pulsed laser beam is a pulsed CO_2 or YAG laser beam.

Fig.1



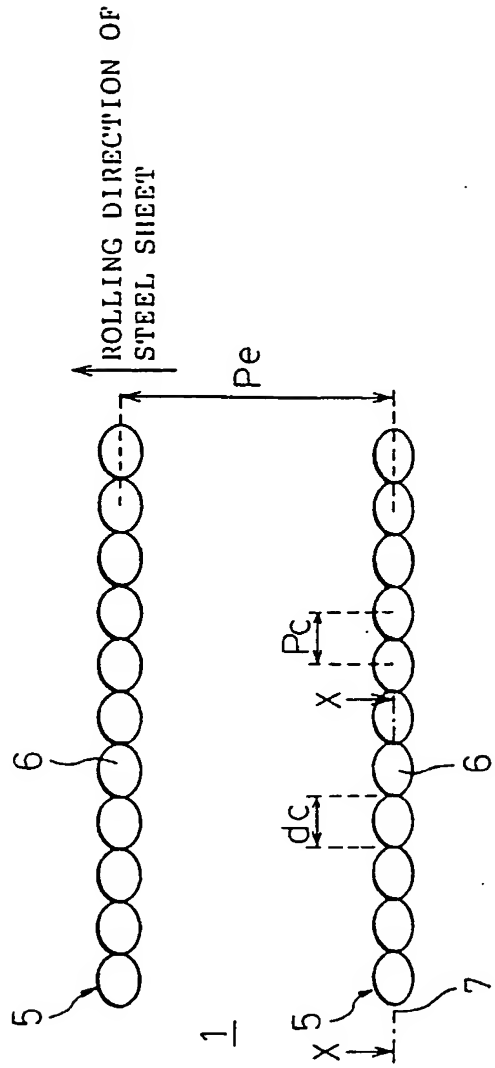


Fig.2(a)

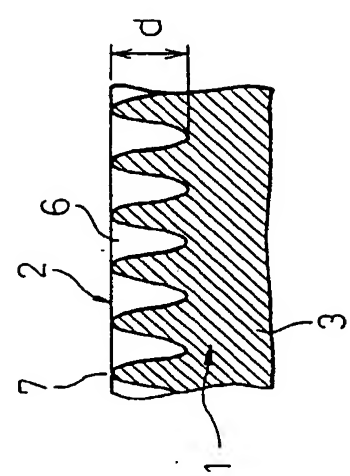


Fig.2(b)

Fig.3

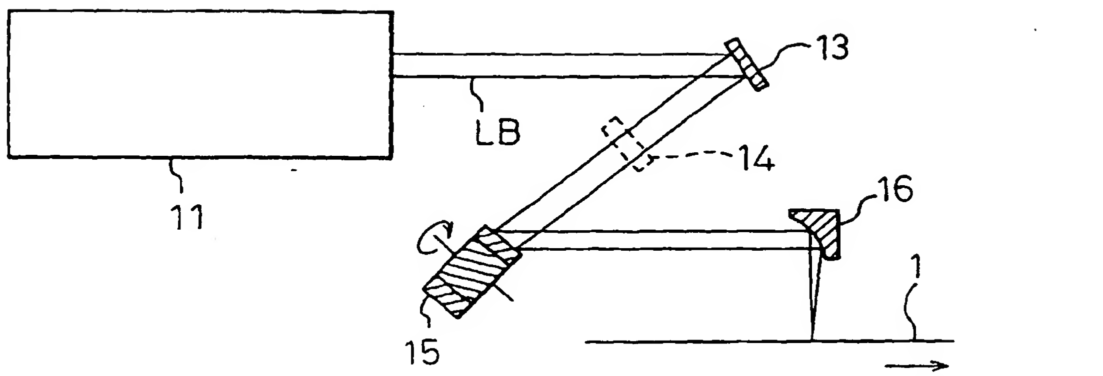

13
LB
14
16
11
1
15
ROLLING DIRECTION OF STEEL SHEET

Fig.4

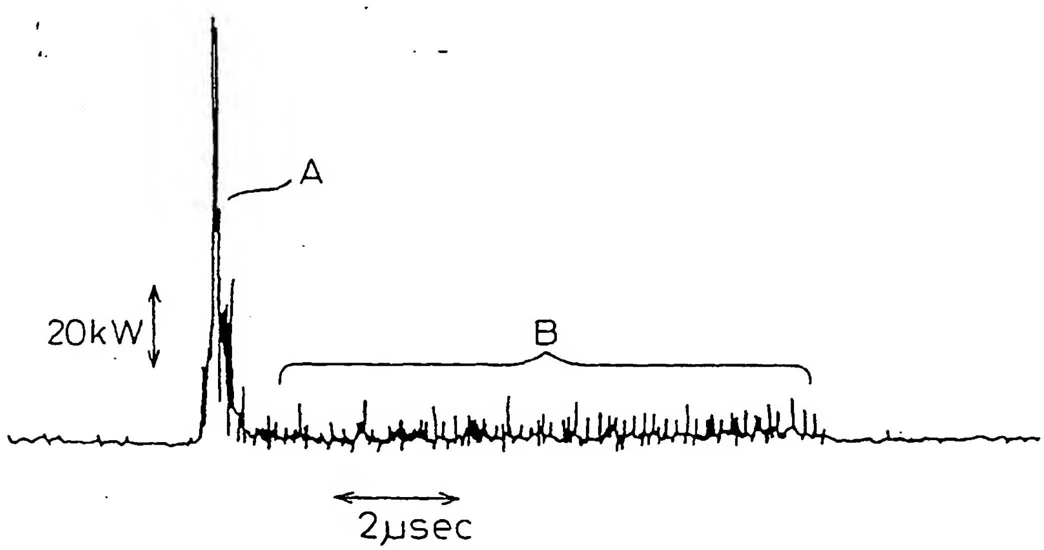

A
20kW
B
2μsec

Fig.5(a)

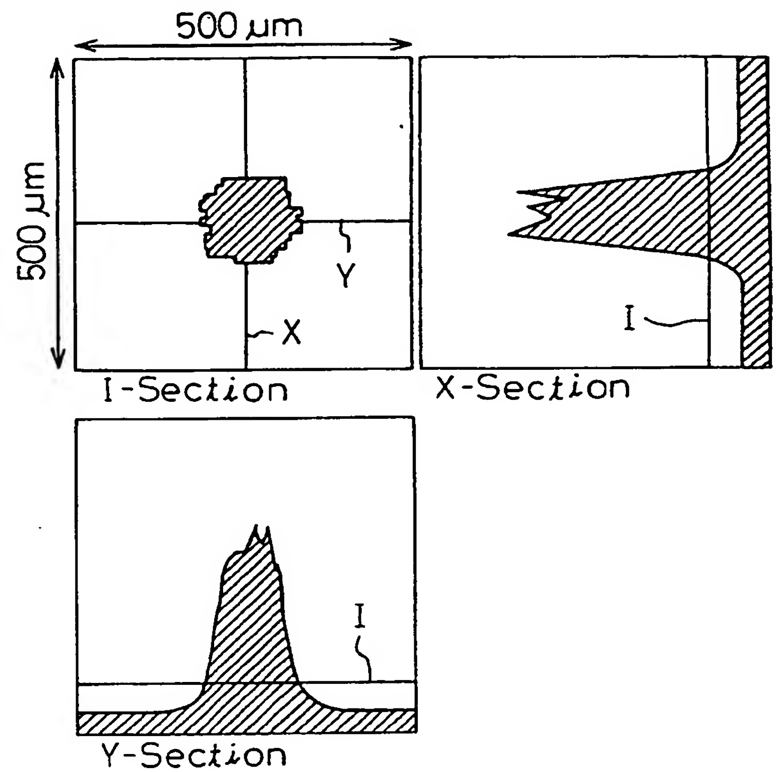

500 µm
500 µm
Y
X
I-Section
I
X-Section
I
Y-Section

Fig.5(b)

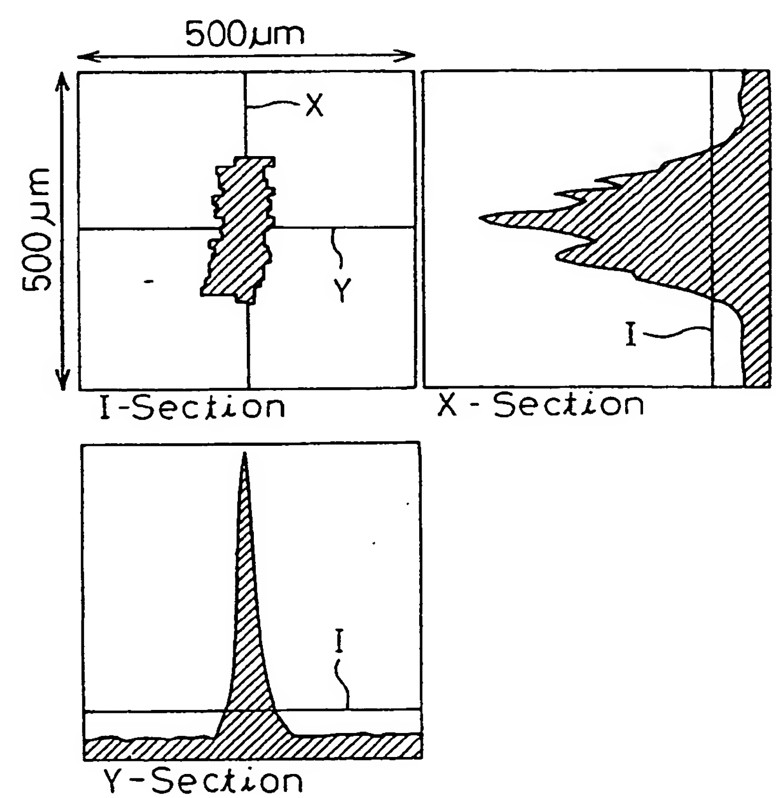

500µm
500µm
X
Y
I-Section
I
X - Section
I
Y-Section

Fig.6(a)

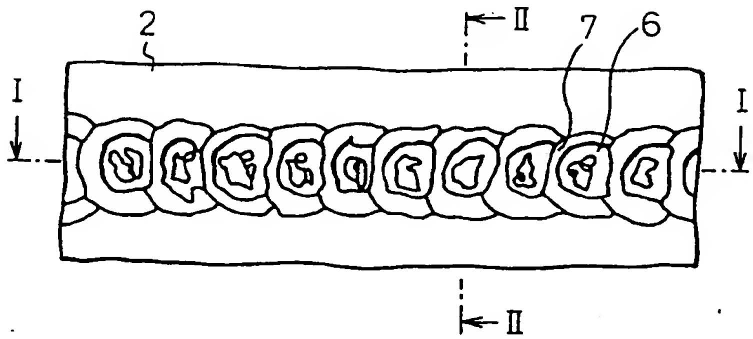


Fig.6(b)

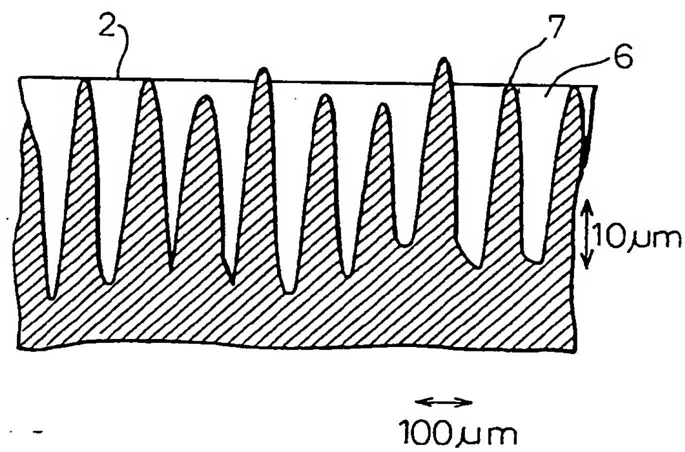


Fig.6(c)

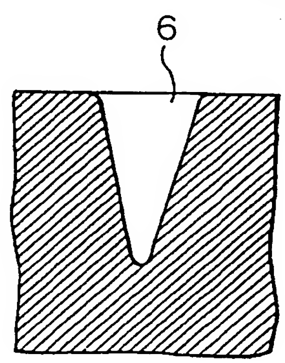


Fig.6(d)

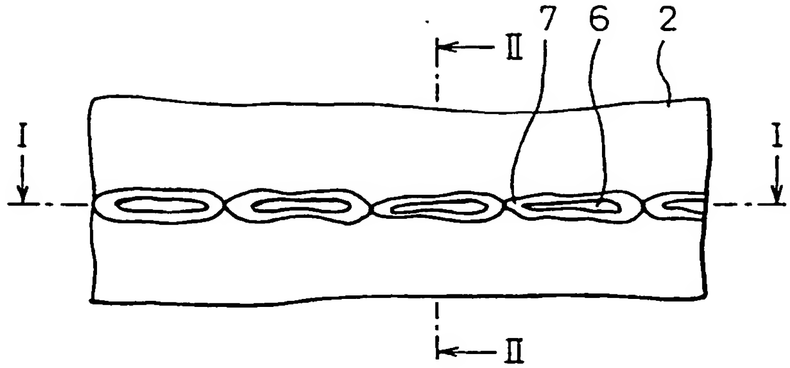


Fig.6(e)

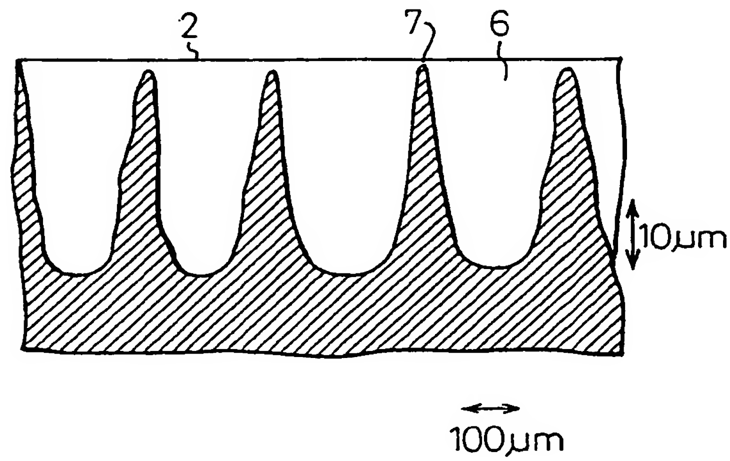


Fig.6(f)

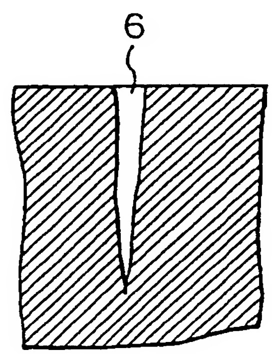


Fig.7(a)

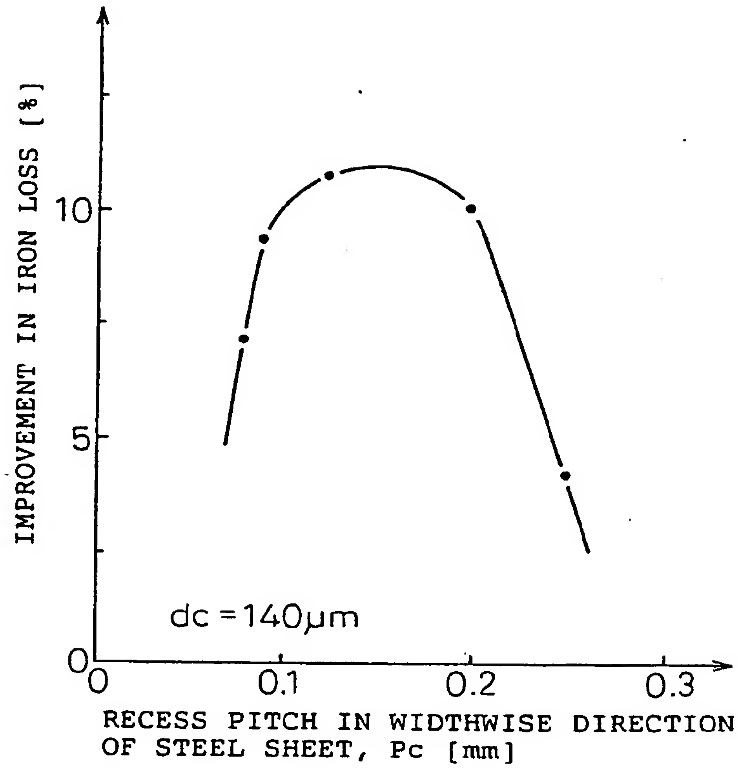
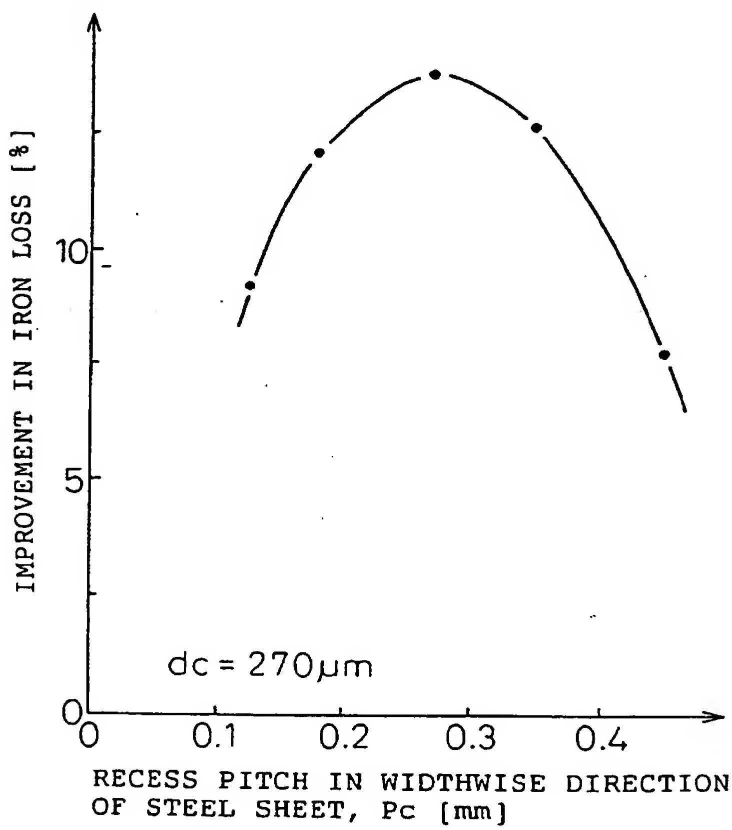

IMPROVEMENT IN IRON LOSS [%]
10
5
0
dc = 140µm
0
0.1
0.2
0.3
RECESS PITCH IN WIDTHWISE DIRECTION OF STEEL SHEET, Pc [mm]

Fig.7(b)


IMPROVEMENT IN IRON LOSS [%]
10
5
0
dc = 270µm
0
0.1
0.2
0.3
0.4
RECESS PITCH IN WIDTHWISE DIRECTION OF STEEL SHEET, Pc [mm]

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP96/03877

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl^6 C21D8/12, H01F1/16

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Int. Cl^6 C21D8/12, H01F1/16

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP, 7-220913, A (Nippon Steel Corp.), August 18, 1995 (18. 08. 95), Claim; column 4, line 34 to column 6, line 22; Figs. 3, 5 (Family: none)	1 - 3
X	JP, 6-57335, A (Nippon Steel Corp.), March 1, 1994 (01. 03. 94), Claim; column 6, line 20 to column 7, line 25 (Family: none)	1 - 3

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier document but published on or after the international filing date
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- "P" document published prior to the international filing date but later than the priority date claimed
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Date of the actual completion of the international search	Date of mailing of the international search report
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